Composites: Part B 60 (2014) 621–626

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Design of microwave plasma and enhanced mechanical properties of thermoplastic composites reinforced with microwave plasma-treated carbon fiber fabric

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ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form 19 December 2013
Accepted 22 December 2013
Available online 1 January 2014

Keywords:
A. Carbon fiber
A. Polymer–matrix composites (PMCs)
A. Thermoplastic resin
B. Strength
E. Compression moulding

ABSTRACT

Microwave plasma equipment was designed and manufactured to improve the interfacial bonding and mechanical interlocking between carbon fiber fabric (CFF) and the polymer matrix. Tensile specimens for the composites reinforced with the as-received and microwave plasma-treated CFFs were prepared using high-speed fabrication with a polymerizable and low-viscosity cyclic butylene terephthalate (CBT) oligomer matrix. Compared with the polymerized CBT (pCBT) matrix, the tensile strengths of the as-received and plasma-treated CFF reinforced composites (CFFRCs) were enhanced by approximately 362.5% and 436.3%, respectively. A high carbon fiber content of 70 vol.% was achieved without introducing pores and/or defects into the CFFRC due to the low viscosity and high impregnation characteristics of the CBT resin. It was confirmed that the microwave plasma can increase the surface roughness of the tested CFF without varying the chemical composition and defect level of the CFF. In addition, the interfacial bonding and mechanical interlocking between the CFF and polymer matrix were improved.

1. Introduction

Because of the increasing need for energy, renewable energy sources, such as biofuel and solar energy, are being adopted as an energy source for transportation. However, the recent escalation of world food prices and a lack of efficiency are hindering the application of renewable energy. One of the fundamental solutions to the energy issue involves decreasing the consumption of the energy by creating lighter methods of transport [1]. Carbon fiber reinforced composites (CFRCs) are one of the promising materials for reducing the weight of vehicles because they are light-weight and have a high specific modulus and good strength properties [2]. Because the use of short CFRCs in automotive materials is limited by their mechanical properties, the application of carbon fiber fabric reinforced composite (CFFRC) would satisfy the properties required by automotive materials [2,3].

In general, CFFRC fabrication methods involve resin transfer molding (RTM) and injection molding (IM) for thermoset and thermoplastic polymer matrices, respectively. In RTM, carbon fiber fabric (CFF) is placed into a metal mold, and a thermoset resin with a low viscosity is injected into the mold. After the injection, the resin is cured [4]. The mechanical and thermal properties of the thermosetting CFFRC are outstanding because the cured resin is not remelted. However, RTM requires a long process time for curing of the thermosetting resin, and the thermosetting CFFRC is not recyclable. In IM, the resin is injected after the CFF is placed into the metal mold. Then, the injected resin is quickly cooled [5,6]. The processing allows for easy shaping for various applications and recycling of the produced thermoplastic CFFRC. Impregnation of the resins into CFF is difficult due to low processability of the thermoplastic resins caused by a rapid increase in the viscosity as the molten thermoplastic resins are cooled. A polymerizable and low-viscosity thermoplastic resin (i.e., cyclic butylene terephthalate (CBT)) overcomes the disadvantages of the two processes [7–12]. When CBT is heated, it can be impregnated into CFF in the form of a low-viscosity liquid. In addition, uniform properties of the thermoplastic CFFRCs can be obtained because the polymerization of the CBT resin is not an exothermic reaction [11,12].

In addition to the speed of the process, the mechanical properties of CFFRC are another important issue in the application of CFFRC in vehicles. The mechanical properties of a CFRC can be significantly enhanced by surface treatments of the carbon fiber (CF) because interfacial bonding between the CF and polymer matrix strongly influences the mechanical properties of CFRC [13–16]. The mechanisms, including mechanical interlocking and adsorption interaction, result in enhancement of the fiber–matrix

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http://dx.doi.org/10.1016/j.compositesb.2013.12.064

interfacial bonding [17]. Plasma technologies have been used in many applications ranging from textiles to fiber reinforced composites to improve mechanical interlocking and adsorption interaction between the CF and polymer matrix [18–22]. Montes-Moran et al. [18,23] and Kowbel and Shan [24] reported that a plasma treatment improved interlaminar shear strength (ILSS). Figueiredo et al. [25] reported that the surface roughness of the CF was increased substantially after plasma treatment, while nitric acid treatment did not substantially change the morphology of the surface of the CF. In this study, CFF was treated with lab-made argon microwave plasma, and the plasma parameters were measured to specify the condition of the plasma treatment. The treated and untreated CFF were made into thermoplastic CFFRCs using a fast manufacturing process with the CBT resin, and the effect of the developed microwave plasma treatment on the mechanical property of the prepared CFFRCs was investigated.

2. Experimental

2.1. Materials

The CBT resin used in this experiment was CBT 160, which was supplied by Cyclics Corporation (NY, USA). The melt range of the resin was from 130 to 150 °C because the resin was composed of two to seven butyl groups in the oligomer mixture. Initially, the molten oligoesters had a viscosity as low as approximately 20 cp. When the resin was heated to a temperature over 160 °C, the viscosity increased rapidly because the entropically driven ring-opening polymerization of the cyclic oligoesters occurred at temperatures higher than 160 °C. The density of the polymerized CBT (pCBT) formed after the polymerization of the oligoesters is 1.3 g/cm^3. CFF (CF-3327EPC, HANKUK CARBON, Korea) used as reinforcement was composed of T-300 grade CF with a density of 1.82 g/cm^3.

2.2. Design for microwave plasma

A schematic of the experimental apparatus is shown in Fig. 1. The plasma was discharged in 22 mm internal diameter quartz tubes. To protect the quart tubes from the heat generated by the plasma discharge, a dual quartz tube was adopted. The internal quartz tubes were enclosed within external quartz tubes that had a 35 mm diameter. In addition, compressed air was passed between the internal and external quartz tubes to cool the quartz tubes. One end of the dual tube system (250 mm in length) was connected to the 1st water-cooled aluminum chamber, and the other end, which was 750 mm in length, was connected to a gas injector, through which 10 lpm of argon gas was injected toward the other end of the dual tube system. The energy source of the plasma discharge was a 2.45 GHz microwave supplied by 1.8 kW magnetron head (GA4002A, Gerling Applied Engineering, Modesto, CA, USA). The microwave energy was transmitted through a waveguide and deposited in the plasma inside the 750 mm end of the dual tube system connected perpendicular to the waveguide and 250 mm from the injector. The load impedance of the microwave was matched by a 3-stub tuner (WR284, Gerling Applied Engineering) to minimize the reflected component of the transmitted microwave. A 2nd water-cooled aluminum chamber, which incorporated a motor driven roller, enabling continuous plasma treatment by drawing the CFF sheet sample toward the 2nd chamber, was connected to the 750 mm end of the dual tube system. The base pressure of the experimental apparatus was measured with an active Pirani vacuum gauge (APG100, Edward korea, Cheonam, Korea), and the pressure during the process was measured with a capacitance manometer (Baratron, MKS instruments, Andover,

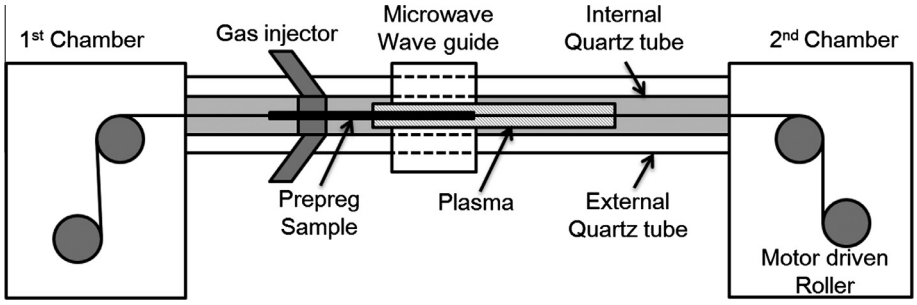

Fig. 1. Schematic representation of the experimental apparatus for the lab-made argon microwave plasma.

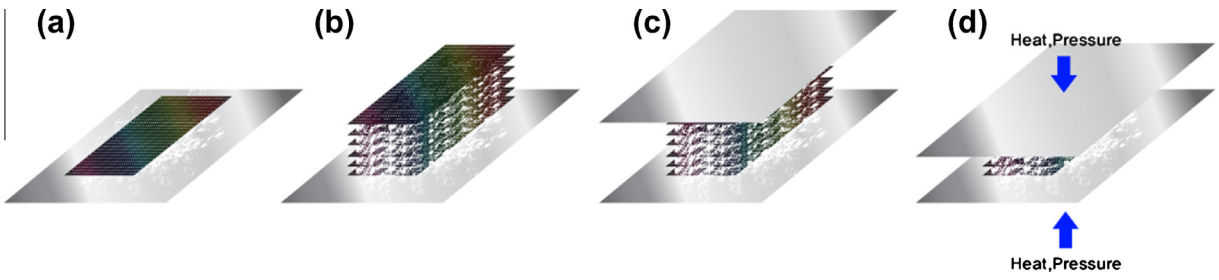

Fig. 2. Schematic diagram of the proposed high speed production of thermoplastic CFFRC. (a) CFF was laminated after an appropriate amount of CBT powder was sprinkled onto the mold, and the CBT powder was sprinkled again over the CFF. (b) The process was repeated to match the target thickness of the specimen. (c) The stacked materials were covered with the steel mold. (d) The specimen was produced by hot pressing under a compression pressure of 1 MPa at 250 °C for 2 min.